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FATIGUE TESTING

An Outline of the Routine Laboratory Tests of Bristol Engines

FAILURE of aero engine components may be due to a number of causes; in a few instances the actual reason for failure may be very obscure, but in the majority of cases it may be fairly accurately attributed either to imperfect material or over-stressing, or a combination of both.

The large majority of failures are, moreover, of a well-defined type and characteristic of a set of conditions in which the stresses imposed are of a fluctuating nature. The most simple form of fluctuating stress is that in which the stress changes from tension through zero to compression, the maximum stress in each direction being equal. This is known as a reversed stress. In some cases the stress may fluctuate from zero to a tension stress, this type being known as a repeated stress.

A third type includes those cases where the stress is never zero, but fluctuates over a range of values above the zero line. This is known as a pulsating stress. In all the above cases one complete reversal of stress is known as a stress cycle. Fig. 1 shows in diagrammatic form the various forms of stress cycles described above. In addition to the simple tension and compressive stress fluctuations more complex stress cycles may occur, such as reversed torsion, reversed bending and combinations of both.

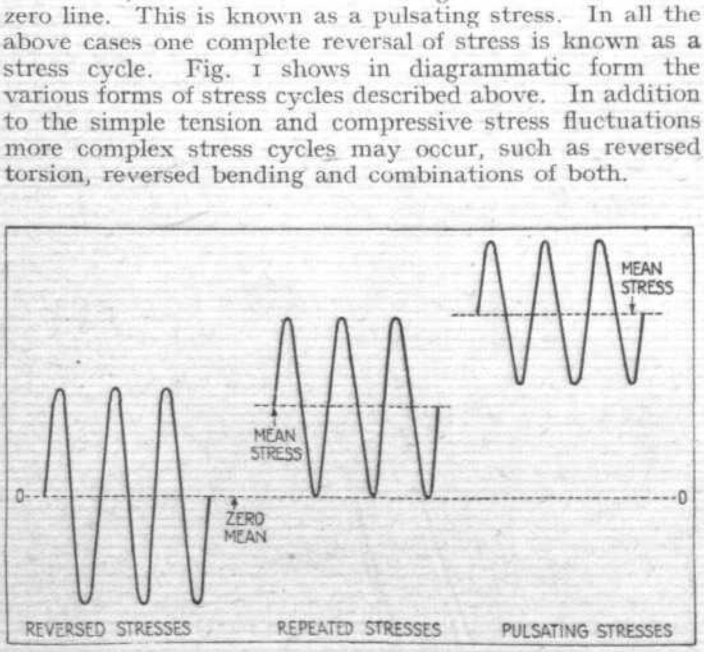


Fig. 1: Various forms of stress cycles.

The type of failure produced by these cycles of stress is known as a fatigue failure, and the actual propagation of the crack through the component may be either extremely slow or fairly rapid, depending upon the degree of over-stress and the material concerned. The crack itself has certain well-defined characteristics and it is usually possible to deduce the initial nucleus of the crack and the speed of propagation from its appearance. A photograph of a typical fatigue crack is shown in Fig. 2.

Fatigue cracks invariably originate at some point of stress concentration in the component; e.g., screw threads, oil holes, sharp radii and similar localities, and it is necessary for the designer so to proportion the component in question as to eliminate these stress-concentrating factors as much as possible. In this respect it might be mentioned that in regard to this point of stress concentration some materials are much more sensitive than others to sharp corners and abrupt changes of section. This property is sometimes known as "notch-sensitiveness."

When an aero engine is designed, the materials of which it is constructed are carefully selected for certain specific purposes. Some components require high strength and resistance to fatigue characteristics; in others good bearing properties are essential, while others again may require to possess good heat conductivity, high thermal expansion and similar features.

It is desirable, where possible, to be able to test the various properties of materials without recourse to long and expensive main engine tests, and it is here that the metallurgical laboratory is able to render such valuable assistance to the complex process of evolving and producing aero engines. Among the various properties and materials investigated by the laboratory, the resistance to fatigue is one of the most important. A great deal of knowledge and practical data that are of the utmost value to the designer may be obtained from the fatigue testing of model sections; the designer can evaluate the stresses involved more accurately and, in addition, considerable expense is saved in avoiding costly main engine experiments. It also forms a very convenient method for quickly obtaining exact information on new and untried material, and can be used to assess the increased strength characteristics of improvements in detail design.

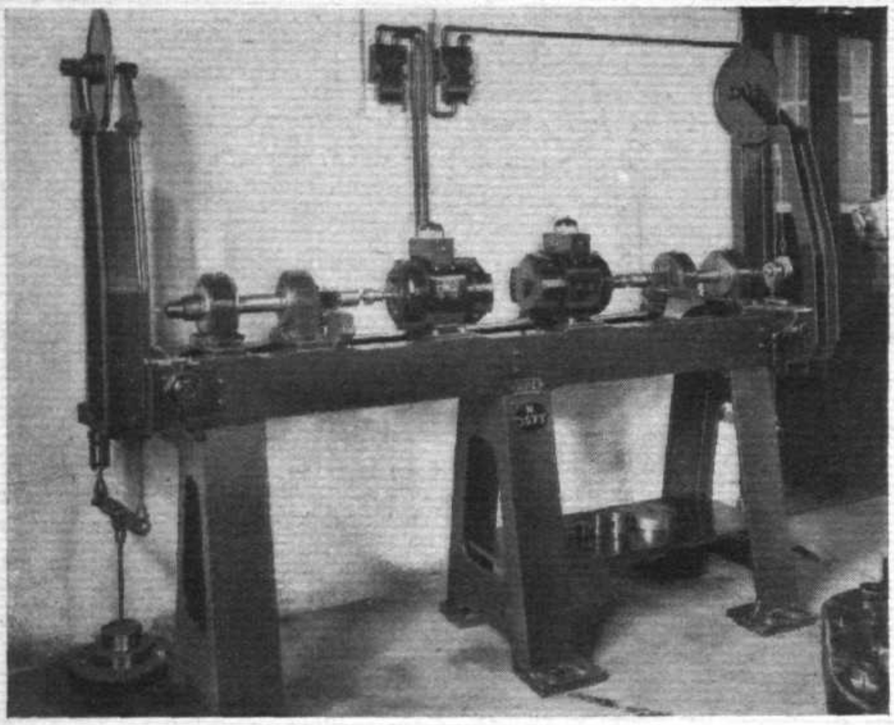
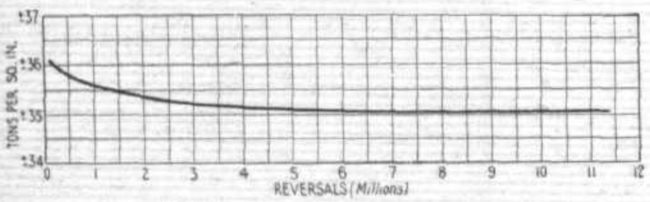
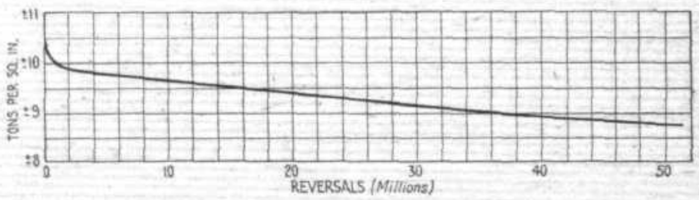


Fig. 2 (above): A typical fatigue crack. In Fig. 3 (left) is shown a Wöhler fatigue testing machine used in the Bristol engine laboratory.

The laboratory of the Bristol Aeroplane Co., Ltd., at Filton, is well equipped with up-to-date apparatus to perform a variety of fatigue tests, and includes the following machines:

Wöhler Fatigue Testing Machine. This machine is illustrated in Fig. 3. The test piece acts as a rotating cantilever, the stress varying from tension to compression





Left, Fig. 4: Stress endurance curve of nickel-chromium molybdenum steel, oil hardened and tempered. Limit of proportionality, 43 tons per sq. in.; 0.2 per cent. proof stress, 56.4 tons per sq. in.; max. stress, 62.2 tons per sq. in.; elongation, 24.8 per cent.; R. of A., 65.0 per cent. Right, Fig. 5: Stress endurance curve of wrought magnesium alloy. Limit of proportionality, 4.0 tons per sq. in.; 0.1 per cent. proof stress, 12.0 tons per sq. in.; max. stress, 20.2 tons per sq. in.; elongation, 19.7 per cent.; R. of A., 32.0 per cent.

every reversal. This machine is of the uniform bending type, a characteristic obtained by specially applied loading, whereby the stress is uniform in the test piece over a length of 1½ inches, instead of concentrated at one point as happens in a singly loaded machine of this type. Uniform loading is particularly useful for testing screw threads and similar components over which the normal stress is evenly distributed. Four of these machines are at present installed in the laboratory; they are driven independently by small electric motors at either approximately 2,000 or 3,000 r.m.p. Figs. 4 and 5 show stress endurance curves obtained from tests made on this type of machine. The curves represent:

(1) A nickel-chromium molybdenum steel heat-treated to give 62.2 tons/sq. in. maximum tensile strength.

(2) A wrought magnesium alloy having a maximum tensile strength of 20.2 tons/sq. in.

Combined Stress-Fatigue Machine. The machine shown in Fig. 6 is the special combined stress-fatigue testing machine designed by the National Physical Laboratory. This actual machine is the first of this type to be installed in an aero engine laboratory. The test piece does not rotate, and it is possible with this machine to obtain reversed bending stresses, reversed torsional stresses or any combination of the two, by varying the relative angle at which the test piece is held. The machine is actuated by a single electric motor at a speed of 2,120 r.p.m

Amsler Repeated Impact Machine. The machine shown in Fig. 7 is the Amsler repeated impact testing machine with which it is possible to obtain impact fatigue data employing tensile, compression or transverse stresses. The machine is operated by a single electric motor and, on account of the staccato and somewhat unpleasant noise it emits when in operation, it is housed in a sound-proof cabinet which incorporates a quickly removable section for inspection purposes.

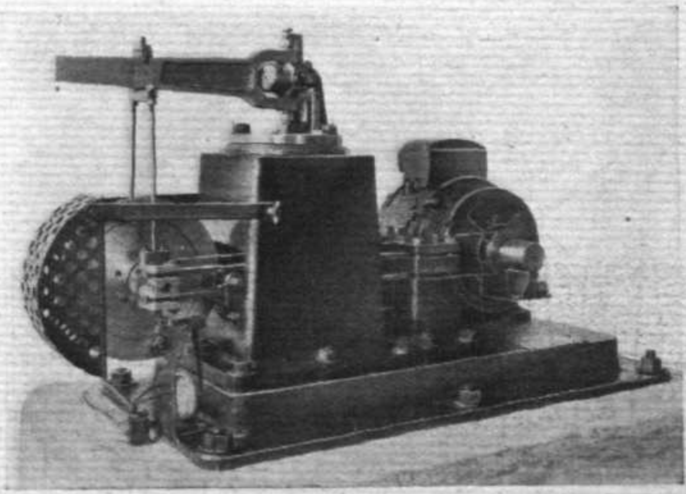


Fig. 6: Combined stress and fatigue machine designed by the National Physical Laboratory.

Crack Detection

Although described previously (*Flight*, March 7, 1935), mention may also be made of the " Magna-Flux " method of fault detection, which is used extensively in the Bristol engine laboratories. The apparatus incorporates a large coil, energised by direct current, a solid core, and adjustable sliding pole pieces. The component to be tested is placed across the gap between the pole pieces after having been thoroughly cleaned. The current is switched on and a liquid called " detector ink " which contains very finely divided particles of iron is poured over the component. If there is a crack, even a very minute one, the iron particles will collect on the edges, owing to the disturbance of the magnetic flux.

It will be obvious that the " Magna-Flux " method of fault detection is applicable to ferrous materials only. There are, however, a large number of engine components which can be examined in this way, such as crankshafts and camshafts, drives, gears and so forth.

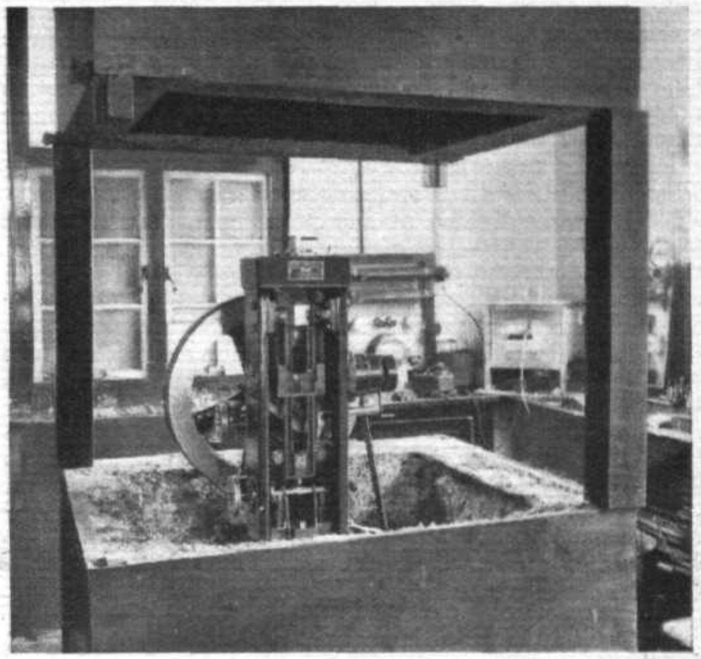


Fig. 7 : Amsler repeated impact machine in the Bristol engine laboratory.

TWO-SPAR CANTILEVER WINGS

A Rapid Method of Obtaining the Stresses in Spars and Skin

By B. B. WALKER, B.Sc.

Introduction

THE cantilever monoplane, having very little parasitic drag, is becoming a very favoured type of design. There are various systems of wing structure, the main problem to be attacked in all of them being that of finding a way of giving sufficient resistance to torsional deflection without undue weight.

One of the commonest and simplest solutions of this is the provision of a skin or wing covering between the spars capable of taking at least shear stress. This, with the spars, forms a tube or set of tubes that can resist torsion. This skin, sometimes forming the whole surface, and sometimes only that portion between the spars, is generally of three-ply wood if the spars are of spruce but of metal if the spars are themselves metal.

The shear stresses in such a skin (composed of a material of which the elasticity is of the same order as that of the spars) are light, and the skin comparatively thin, if it is made just thick enough to keep the twist of the wing under load down to safe limits. At the same time, because of the approach to equalisation of bending deflection of the spars, the stresses in these are lightened by the presence of the skin.

If, however, the skin were designed to take any appreciable amount of *bending* stress it would have to be thickened or stiffened in such a way that its weight would be enormously increased. As a consequence this is not usually done (except in wings in which the skin takes the bulk of the stress and the spars very little), and the problem before the calculator of stress is the finding of a method that assumes the spars alone to resist the bending moments on the wing, while the twist is resisted partly by differential bending of the spars and partly by resistance of the tube formed by the spars and skin. The determination of the proportions in which this division will take place to give equilibrium presents the greatest difficulty, as it is a case of a redundant structure, and the ordinary methods of strain-energy are not applicable.

A first rough method that has been applied is to work out the bending moments on the spars as though there were no skin, and then to assume a certain percentage of bending moment transferred from one spar to the other, the value being empirically decided upon from data as to the position of the centre of pressure and from previous experience. Such a method gives no figure for the stress in the skin, and is necessarily very crude in any case of the slightest novelty in the proportions of spar sizes and skin thicknesses, or in properties of wing section, and a little investigation shows that an even percentage of transference throughout the wing is erroneous.

The more exact methods, of which perhaps the best known is that indicated by Prof. Roxbee Cox in R. & M. 1617, first evaluate the bending moments that would be given to the spars by pure flexure (no twisting deflection) and then by means of expressions based on the average properties of a number of wings, find the bending moments to be added or subtracted for the torsion and the corresponding stress in the skin. In the publication mentioned, the torsion is found by first finding a " flexural line," which is the line upon which the load would have to be placed if there were to be no twist.

For this line two differentiations and integrations of curves are necessary. The line is found for the air load alone, after which the division of the torsion due to this is found. Any torques concentrated at one or two points, such as those due to overhanging engines, are arrived at separately and their effects superimposed.

Such methods thus comprise two portions, the first consisting of the division of the applied loads into (*a*) loads producing pure flexure or similar curvatures of the spars and (*b*) a set of torques, and the second the determination of the effect of these torques. Further, each portion may have to be divided into a calculation for the air load and one for concentrated torques if the necessities of the application of approximations demand it.

In this article there is shown first in Part I a method of finding the system of torques, which is quick and simple and may be applied to the air loads alone or to these combined with those due to concentrated weights. It involves

only one differentiation of a curve, so that cumulative errors are avoided. (The finding of the effects of the pure bending is a simple matter in any method, as for equal curvatures of the spars at any point in the span the spars must be subject to bending moments proportional to their moments of inertia.)

The term "residual torque" is employed in the same sense as in R. & M. 1617 (mentioned above). If we consider the wing divided at any point by a plane at right angles to the centre line of the spars (these being parallel) the loads described as (*a*) above on the section outboard of the plane give a certain total bending moment and shear on the wing structure at the plane. The torques (*b*) on the outboard section give a twisting moment which must be added to give the entire set of actual forces on the inboard section. This couple is the residual torque.

The method of Part I may thus be used to find the curve of residual torque throughout the wing, and other methods (such as that of R. & M. 1617) used for finding how much of this is taken by the spars in differential bending and how much of the residual torque is taken by the skin in shear.

In Part II will be described a graphical method of directly finding the stresses in skin and spars (taking the usual assumption of shear stress only in the skin) without determining the residual torque expressed as a torque but making use of a curve of what is termed here the "unbalanced bending moment," the plotting of which enters into the method of Part I.

In this direct method of Part II the torques of concentrated weights are taken into account with the others due to air loads, as the method begins by the plotting of bending moment curves for the spars as though no skin were present.

Parallel spars are assumed in both parts, but an extension to the case of converging spars could probably be made without much difficulty.

The methods rest on a consideration of the bending moment transferred from one spar to the other by the skin. A "transferred bending moment," found graphically, is added or subtracted to the "independent bending moments," *i.e.*, those given if no skin were present.

PART I—A METHOD OF FINDING THE "RESIDUAL TORQUE"

General

As an alternative to the method of finding the "flexural line" of a cantilever wing, the residual torque* curve for a given system of loading may be found by the following method.

This is quicker than calculation, as the calculation of the flexural line takes some considerable time and this alternative method also gives moment curves that are useful in analysing the spar stresses and in comparing these with those produced by other cases of loads.

These curves also enable a graphical method of finding the actual spar stresses to be adopted. In this method (separately described) concentrated torques such as those due to wing engines may be exactly taken into account. The method is first described and the proof follows.

Method

The air load, c.p. locus, wing weight and any other loads being given, these are converted into distributed and concentrated loads on the spars (as in most usual systems of stressing for biplanes and strutted monoplanes) as though the spars were acting independently with no skin or other means of transferring load from one to the other.

The shear force and bending moment diagrams for each spar are then found for this independent action. These will be referred to as the "independent" shear forces and bending moments. The ordinates of the independent front and rear spar bending moments are then added to give a curve of the total bending moment on the wing.

If at any section of the wing the I_F = the moment of inertia of the front spar; and the I_R = the moment of inertia of the rear spar, values are found for $\dfrac{I_R}{I_F + I_R}$ (or "R" in Report No. A.D. 3044) and the curve drawn.

The curve is then drawn for $\dfrac{M\,I_F}{I_F + I_R}$. This is here referred to as the "balanced" bending moment for the front spar, $\dfrac{M\;\;I_R}{I_F + I_R}$ being known as the "balanced" bending moment for the rear spar (only one need be found).

The differences between the ordinates of the independent front spar bending moment and the front spar balanced bending moment, give a curve of bending moments, which will be termed the "unbalanced bending moments" at their corresponding points. The slope of this curve at any point, multiplied by the distance between the spars, gives the residual torque.

Thus if M_{IF} is the independent bending moment on the front spar at any point, and M, I_F and I_R have their previous significance,

$$\text{Unbalanced b.m.} = M_{IF} - M\frac{I_F}{I_F + I_R} \quad \cdots \quad \cdots \quad (1)$$

$$\text{and residual torque} = d\,.\frac{d}{dx}\left(M_{IF} - M\frac{I_F}{I_F + I_R}\right) \quad \cdots \quad (2)$$

where *d* is the distance between spar centres, and *x* is the distance of any point from the wing tip.

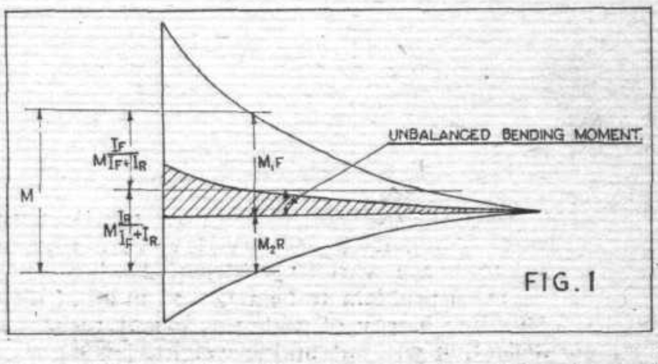


FIG. 1

The unbalanced bending moment at any point can also be found from the differences of the rear spar independent bending moment and the rear spar balanced bending moment, but the signs of the terms must be reversed to give a correct sign for the result.

Thus if M_{IR} is the rear spar independent bending moment, and we write

$$\text{Unbalanced b.m.} = -M_{IR} + \frac{M\,I_R}{I_F + I_R} \quad \cdots \quad \cdots \quad (1a)$$

this b.m. is given with the same sign as in (1) and the residual torque may be found from it.

A convenient way of representing these bending moments is that shown in Fig. 1 in which the independent bending moments are plotted with opposite signs on the same axis. The addition of them can then be made graphically, and a graphical check can be made on one of the balanced bending moments after the other is calculated, as the sum of these is also M.

Proof

The residual torque at any section of the wing is the couple which, with certain forces giving no torsional deflection, will complete the system of forces acting at that section due to the loads applied.

The two "balanced" bending moment systems defined by the curves of $M\dfrac{I_F}{I_F + I_R}$ and $M\dfrac{I_R}{I_F + I_R}$ and their accompanying shear forces, applied respectively to the front and rear spars, give the same deflection to these spars throughout their length, with no torsional deflection.

* As defined in the Introduction.